

## Burr formation and hole quality when drilling titanium and aluminium alloys

Abdelhafeez, Ali; Soo, Sein; Aspinwall, David; Dowson, Anthony; Arnold, Dick

DOI:

[10.1016/j.procir.2015.08.019](https://doi.org/10.1016/j.procir.2015.08.019)

License:

Creative Commons: Attribution-NonCommercial-NoDerivs (CC BY-NC-ND)

*Document Version*

Publisher's PDF, also known as Version of record

*Citation for published version (Harvard):*

Abdelhafeez, A, Soo, S, Aspinwall, D, Dowson, A & Arnold, D 2015, 'Burr formation and hole quality when drilling titanium and aluminium alloys', *Procedia CIRP*, vol. 37, pp. 230-235.  
<https://doi.org/10.1016/j.procir.2015.08.019>

[Link to publication on Research at Birmingham portal](#)

### **Publisher Rights Statement:**

Checked November 2015

### **General rights**

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

### **Take down policy**

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact [UBIRA@lists.bham.ac.uk](mailto:UBIRA@lists.bham.ac.uk) providing details and we will remove access to the work immediately and investigate.

CIRPe 2015 - Understanding the life cycle implications of manufacturing

## Burr formation and hole quality when drilling titanium and aluminium alloys

A.M. Abdelhafeez<sup>a</sup>, S.L. Soo<sup>a,\*</sup>, D.K. Aspinwall<sup>a</sup>, A. Dowson<sup>b</sup>, D. Arnold<sup>c</sup><sup>a</sup>*Machining Research Group, School of Mechanical Engineering, University of Birmingham, Birmingham B15 2TT, UK*<sup>b</sup>*Airbus Operations Ltd., New Filton House, Filton, Bristol BS99 7AR, UK*<sup>c</sup>*Mapal Ltd., Old Leicester Road, Rugby CV21 1DZ, UK*\* Corresponding author. Tel.: +44-121-414-4196/4201; fax: +44-121-414-4201. E-mail address: [s.l.soo@bham.ac.uk](mailto:s.l.soo@bham.ac.uk)

### Abstract

Following a brief review of key factors affecting burr size and hole quality, the paper details experimental work involving the drilling of Ti-6Al-4V titanium alloy together with Al7010-T7451 and Al2024-T351 aluminium alloys. Chemical vapour deposited (CVD) diamond coated carbide drills were used for the aluminium workpieces while uncoated carbide tools were employed for the titanium material. An experimental design based on response surface methodology was implemented to identify the effects of cutting speed and feed rate (each at 3 levels) on burr size, hole diameter and out of roundness as well as tool flank wear. Exit burr size was smallest when operating at the intermediate feed rate level for all three workpiece materials, with reductions in burr height of up to 50% and 75% for the titanium and aluminium alloys respectively. Out of roundness did not exceed 0.03 mm while the deviation on hole diameter was less than 0.04 mm in all trials, even after drilling 60 holes.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

[\(http://creativecommons.org/licenses/by-nc-nd/4.0/\)](http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the organizing committee of CIRPe 2015 - Understanding the life cycle implications of manufacturing

*Keywords:* Drilling; Burr formation; Aerospace alloys

### 1. Introduction

Burr formation and poor hole geometrical quality can be detrimental to fatigue life as well as hinder the assembly and functionality of drilled components. This generally necessitates the application of costly additional operations such as reaming and deburring. The generation of burrs is typically influenced by various parameters including tool geometry and material, workpiece material properties, part geometry and process conditions [1]. Feed rate and cutting speed however are the easiest factors to control for burr minimisation, the rest of the aforementioned parameters being largely application dependent.

Numerous researchers have investigated the effects of varying cutting speed and feed rate with respect to the reduction of burr size in drilling. Sofronas and Taraman [2] and Ko et al. [3] identified feed rate as being the most significant parameter affecting burr size with a proportional

relationship when drilling different steels (AISI 1018 and SM45C alloy). Conversely, Pande and Relekar [4], Stein and Dornfeld [5] as well as Karnik and Gaitonde [6], reported a non-linear trend between burr size and feed rate when drilling similar workpiece materials. Dornfeld et al. [7] however showed that both feed rate and cutting speed had limited influence on burr size when drilling Ti-6Al-4V, although this could be attributed to the restricted range of cutting speed (6-10 m/min) and feed rate (0.04-0.20 mm/rev) levels employed in the experiments. Subsequent work by Kim et al. [8] involving two types of stainless/alloy steels (AISI 304L and 4118), led to the development of an experimentally based burr control chart which suggested that feed rate and the interaction between feed rate and cutting speed had a significant impact on burr formation.

Drilled hole geometrical quality is primarily quantified by the out of roundness/cylindricity and diameter accuracy parameters. Early investigations of hole quality revealed

that use of low feed rate reduces out of roundness and enhances alignment of the hole [9] while hole diameter deviation was reported to increase with feed rate and cutting speed [10]. In contrast, Abele et al. [11] showed that cutting speed had the greatest effect on hole roundness while the contribution of feed rate was marginal. In addition to the relatively narrow range of feed rates assessed (on average ranging from 0.07- 0.16 mm/rev), the majority of published work precludes the use of statistical analysis techniques to correlate the influence of drilling conditions on resulting burr size and hole quality. This in part explains the contradictory conclusions reported in the literature.

The present paper details results from statistically designed experiments investigating the effect of cutting speed and feed rate on burr size, hole quality and tool wear following through hole drilling of aerospace grade titanium and aluminium based alloys.

## 2. Experimental work

### 2.1. Workpiece material, tooling and test procedures

Three different workpiece materials were evaluated including an annealed Ti-6Al-4V titanium alloy having a tensile/ultimate yield strength of 825/895 MPa, together with 2 different solution treated and aged aluminium alloys; 7010/7050-T7651 and 2024-T351, having tensile/ultimate yield strengths of 450/520 and 290/430 MPa respectively. Dimensions of the strip workpiece specimens for hole quality and surface integrity assessment were 17 x 120 x 6 mm (width x length x height), while square workpiece plates 120 x 120 x 6 mm were used for tool wear trials. The tool life/end of test criterion was a flank wear of 0.1 mm or a maximum of 60 drilled holes.

The cutting tools used were twin fluted, 6.35 mm diameter solid WC twist drills supplied by MAPAL Ltd., with geometry and coating details listed in Table 1. Tool overhang was 57 mm in all trials with run-out < 10 µm.

Table 1. Drill geometry and coating details.

Factor	Workpiece material	
	Ti-6Al-4V	AA7010/AA2024
Product code	MEGA-Stack-Drill-AF-C/T	MEGA-Stack-Drill-AF-A/C
Drill point angle	135°	120°
Drill helix angle	34°	34°
Point geometry	Split point with gashed/thinned chisel	Split point with gashed/thinned chisel
No. of margins	3	2
Tool coating	Uncoated	CVD diamond

All tests were carried out on a Matsuura FX5 high speed machining centre with a maximum spindle speed of 20,000 rpm rated at 15 kW and variable feed rate control of up to 15 m/min. The strip specimens were held in a bespoke fixture mounted on a Kistler drilling dynamometer (model 9273) connected to Kistler 5011A charge amplifiers, with data recorded and processed on a computer using

DynoWare software. The plate workpieces were clamped onto a drilling jig with an array (10 x 10) of pre-fabricated 9 mm diameter clearance holes. Trials were undertaken wet using Hocut 3380 water based emulsion delivered externally (flood) at a flow rate of 52 l/min.

Assessment of hole out of roundness and diameter was carried out on a Talyrond 300 by sampling 2000 data points around the hole circumference at two pitch planes (entry, exit) for the first hole and subsequently every ten holes. Hole diameter was calculated based on the least-square circle fit of the recorded data points. Exit burr height was measured using an Alicona InfiniteFocus G5 optical microscope at 8 equally-spaced positions around the hole periphery with an average calculated over the first 5 holes drilled as described by Kim et al. [8] and Min et al. [12], in order to minimise the influence of tool wear on the results. Drill flank wear measurement was performed using a Wild M3Z tool-maker's microscope equipped with a movable stage having digital micrometers (1 µm resolution) and digital camera for image capture.

### 2.2. Test parameters and experimental array

Tables 2 and 3 detail the variable factors together with levels of feed rate and cutting speed selected based on recommendations from the tool supplier. Response surface methodology with a face centred central composite design was employed where the minimum recommended central runs required to achieve stable variance of the predicted responses was two [13]. Therefore, a total of ten tests were performed for each workpiece material according to the test array listed in Table 4. Statistical analysis of the results was performed using Minitab software.

Table 2. Variable parameters for drilling AA7010/AA2024 alloys.

Factor	Level -1	Level 0	Level 1
Cutting speed (m/min)	50	100	150
Feed rate (mm/rev)	0.08	0.16	0.24

Table 3. Variable parameters for drilling Ti-6Al-4V alloy.

Factor	Level -1	Level 0	Level 1
Cutting speed (m/min)	10	20	30
Feed rate (mm/rev)	0.07	0.14	0.21

Table 4. Experimental array for each material.

Test no.	Cutting speed level	Feed rate level
1	1	-1
2	0	0
3	1	1
4	-1	-1
5	-1	1
6	1	0
7	-1	0
8	0	1
9	0	-1
10	0	0

### 3. Results and discussion

#### 3.1. Exit burr formation

Figure 1 shows the response surface plot for average exit burr height with respect to cutting speed and feed rate over the first five holes drilled in Ti-6Al-4V.

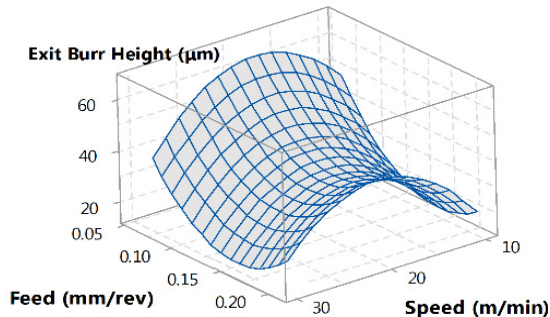


Figure 1. Exit burr height vs. cutting speed and feed rate for Ti-6Al-4V.

A highly non-linear relationship between exit burr height and the cutting parameters was observed, which is represented mathematically by the second order regression model in Equation 1. Burr size was smallest when operating at the intermediate feed rate of 0.14 mm/rev and highest cutting speed of 30 m/min.

$$\text{Exit Burr Height (Ti)} = 53.0 + 8.24 \text{ Speed} - 1203 \text{ Feed} - 0.2254 \text{ Speed}^2 + 3411 \text{ Feed}^2 + 4.64 \text{ Speed*Feed} \quad (1)$$

The corresponding analysis of variance (ANOVA) taking account of the regression equation is detailed in Table 5, which shows that feed, feed<sup>2</sup> and speed<sup>2</sup> had a major influence on hole exit burr size (statistically significant at the 5% level), with associated percentage contribution ratios (PCR) of 28.1%, 47.9% and 26% respectively. The calculated error (or residual) consisted of the model 'lack-of-fit' and 'pure error' components. The former was not significant, indicating that the variations in responses were adequately represented, with a calculated R<sup>2</sup> or coefficient of determination of 96.57%. The latter relates to the difference in measurements of the central runs, which was also not significant.

Table 5. ANOVA for exit burr height model in Ti-6Al-4V.

Source	DF	Adj SS	Adj MS	F	P	PCR
Speed	1	9.37	9.37	0.45	0.539	0.47%
Feed	1	704.17	704.17	33.84	0.004	28.1%*
Speed <sup>2</sup>	1	1185	1185	56.95	0.002	47.9%*
Feed <sup>2</sup>	1	651.86	651.86	31.33	0.005	26%*
Speed*Feed	1	42.25	42.25	2.03	0.227	0.88%
Error	4	83.23	20.81			
Lack-of-Fit	3	81.23	27.08	13.54	0.197	
Pure Error	1	2	2			
Total	9	2427.02				

\*Significant at the 5% level

Figure 2 depicts the response surface plot for exit burr height against feed rate and cutting speed variation in AA7010 workpieces. As with Ti-6Al-4V, burr height was found to be at a minimum when drilling with the intermediate feed rate of 0.16 mm/rev and cutting speed of 150 m/min.

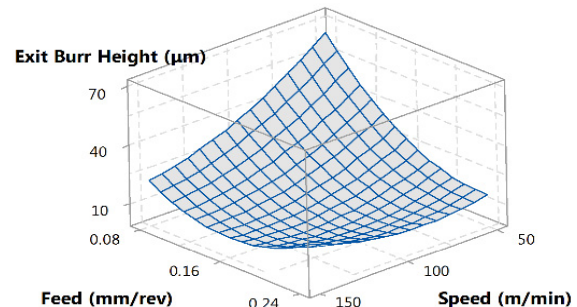


Figure 2. Exit burr height vs. cutting speed and feed rate for AA7010.

The regression model describing the response is outlined in Equation 2 with a R<sup>2</sup> of 87.5%, which indicates a relatively good correlation with the data.

$$\text{Exit Burr Height (AA7010)} = 282.6 - 1.110 \text{ Speed} - 2186 \text{ Feed} + 0.00111 \text{ Speed}^2 + 4507 \text{ Feed}^2 + 4.10 \text{ Speed*Feed} \quad (2)$$

Table 6 details the ANOVA for exit burr height in AA7010 and shows that feed rate was the only significant factor (at the 5% level) but with a moderate PCR of 27.8%.

Table 6. ANOVA for exit burr model in AA7010.

Source	DF	Adj SS	Adj MS	F	P	PCR
Speed	1	513.37	513.375	5.37	0.081	13.6%
Feed	1	950.04	950.042	9.94	0.034	27.8%*
Speed <sup>2</sup>	1	112.01	112.012	1.17	0.34	0.5%
Feed <sup>2</sup>	1	390.01	390.012	4.08	0.113	9.6%
Speed*Feed	1	637.56	637.563	6.67	0.061	17.6%
Error	4	382.22	95.554			
Lack-of-Fit	3	377.72	125.906	27.98	0.138	
Pure Error	1	4.5	4.5			
Total	9	3071.22				

\*Significant at the 5% level

The response surface plot showing the influence of feed rate and cutting speed on exit burr height in AA2024 is detailed in Figure 3. The regression relationship between exit burr height and operating parameters is given by Equation 3 with a R<sup>2</sup> of 96.2%.

$$\text{Exit Burr Height (AA2024)} = 116.2 + 0.676 \text{ Speed} - 1423 \text{ Feed} - 0.00218 \text{ Speed}^2 + 3852 \text{ Feed}^2 - 1.008 \text{ Speed*Feed} \quad (3)$$

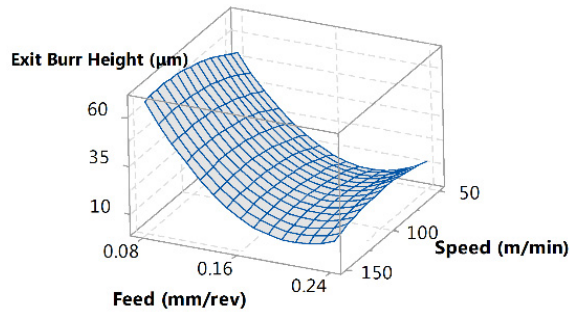


Figure 3. Exit burr height vs. cutting speed and feed rate for AA2024.

As with the AA7010 material, feed rate was found to be the only statistically significant factor affecting exit burr size, with a PCR of 63.8%, see ANOVA in Table 7.

Table 7. ANOVA for exit burr height model in AA2024.

Source	DF	Adj SS	Adj MS	F	P	PCR
Speed	1	94.51	94.51	1.97	0.233	0.9%
Feed	1	3260.84	3260.84	68.11	0.001	63.8%*
Speed <sup>2</sup>	1	69.1	69.1	1.44	0.296	0.4%
Feed <sup>2</sup>	1	1417.99	1417.99	29.62	0.006	27.2%
Speed*Feed	1	65	65	1.36	0.309	0.3%
Error	4	191.51	47.88			
Lack-of-Fit	3	186.22	62.07	11.75	0.21	
Pure Error	1	5.28	5.28			
Total	9	5034.11				

\*Significant at the 5% level

For all 3 workpiece materials, feed rate was found to have a significant effect on hole exit burr height, which agreed with published data [2, 3, 6]. In addition, larger exit burrs were evident when drilling at the low and high feed rates levels, the former as a result of ploughing, as the cutting edge radius (0.16 and 0.30  $\mu\text{m}$  for the uncoated and coated drills respectively) approached the feed rate value, thereby increasing material deformation and hence burr formation at hole exit [5]. Under high feed rate operation, the increased thrust forces is known to yield higher burr size [4].

### 3.2. Hole accuracy

Figure 4 details the average deviation in hole diameter from the nominal value (6.35 mm) over the duration of each test (60 holes drilled). All the holes analysed were oversized by 5 to  $\sim 40 \mu\text{m}$ . Furthermore, the diameter at hole entry was found to be larger than the exit location for all trials, which suggests the possibility of drill 'wander' on contact with the workpiece [14]. Similar oversized hole profiles were reported by Kuo et al. [15] when drilling multi-layer stacks involving Ti-6Al-4V/CFRP/AA7010. Although not shown here, the ANOVA calculations revealed that none of the individual factors (feed rate and

cutting speed) or interactions were statistically significant with regard to hole diameter accuracy for any of the workpiece materials tested.

Figure 5 shows the average hole out of roundness for the 3 workpiece materials in each test after drilling 60 holes. Although all of the values were  $< 30 \mu\text{m}$ , the associated statistical analysis indicated that none of the variable factors or interactions had a significant influence on hole out of roundness. Additionally, the response surface regression model demonstrated a poor fit, with the  $R^2$  value less than 50%.

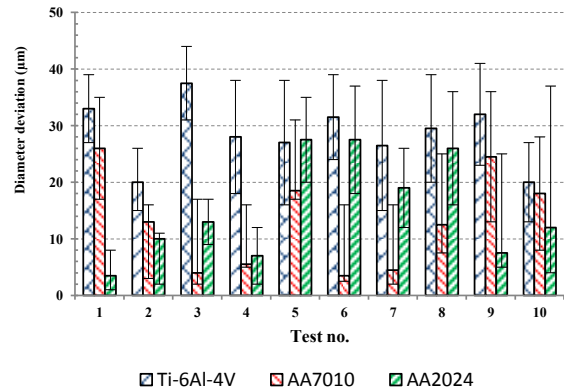


Figure 4. Average hole diameter deviation over experiment duration.

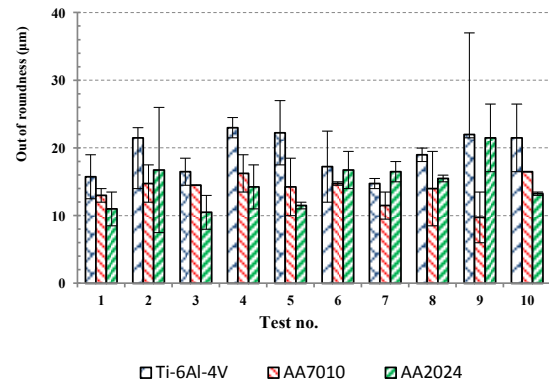


Figure 5. Average hole out of roundness over experiment duration.

Figure 6 shows the out of roundness polar plots for the first holes drilled in Ti-6Al-4V workpieces at the highest (Test 3) and lowest (Test 4) combination of cutting speed and feed rate. A five-lobed profile was apparent at hole entry, but with a more circular shape observed at hole exit, which could be attributed to damping of the low frequency tool vibration deeper into the hole. Figure 7 and Figure 8 display the corresponding out of roundness polar plots for the first holes drilled in AA7010 and AA2024 workpieces respectively. Here, the oval profiles seen at hole entry evolved into tri-lobed profiles at hole exit, the former



probably being caused by wandering of the tool as it entered the workpiece.

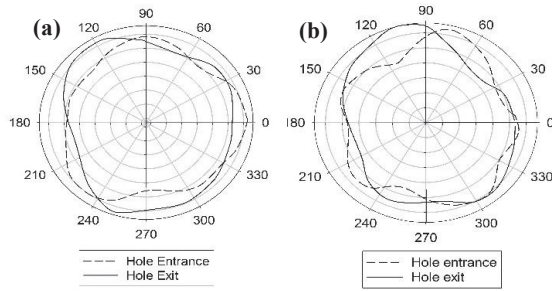


Figure 6. Out of roundness profiles for the 1<sup>st</sup> hole in Ti-6Al-4V at cutting speed and feed rate of; (a) 30 m/min, 0.21 mm/rev, (b) 10 m/min, 0.07 mm/rev.

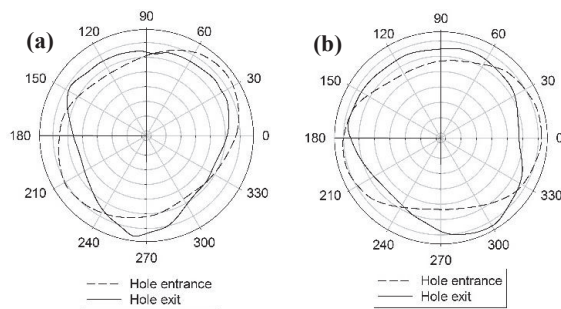


Figure 7. Out of roundness profiles for the 1<sup>st</sup> hole in AA7010 at cutting speed and feed rate of; (a) 150 m/min, 0.24 mm/rev, (b) 50 m/min, 0.08 mm/rev.

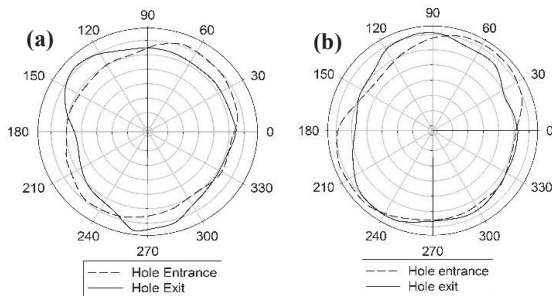


Figure 8. Out of roundness profile for the 1<sup>st</sup> hole in AA2024 at cutting speed and feed rate of; (a) 150 m/min, 0.24 mm/rev, (b) 50 m/min, 0.08 mm/rev.

### 3.3. Tool wear

None of the drills employed in trials involving the aluminum alloys (AA2024 and AA7010) exhibited any discernible wear on the flank face even after 60 holes irrespective of cutting parameters, see example in Figure 9 from Test 3 (highest cutting speed and feed rate) for both material grades.

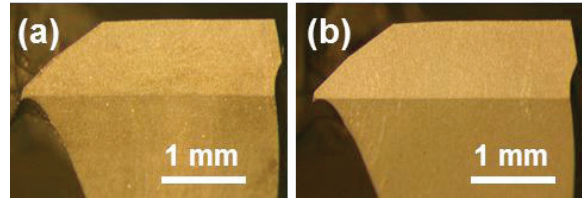


Figure 9. Tool flank wear images after 60 holes in; (a) Test 3 of AA7010. (b) Test 3 of AA2024.

In contrast, relatively low levels of abrasion dominated flank wear (not exceeding 30  $\mu\text{m}$ ) were evident on tools following the drilling of Ti-6Al-4V, see Figure 10. The response surface plot for flank wear at test cessation is shown in Figure 11 while the associated regression function is expressed in Equation 4 having a  $R^2$  value of 84.4%.

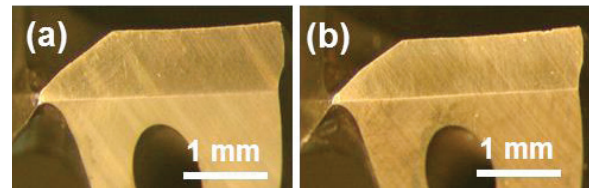


Figure 10. Tool flank wear images after 60 holes in; (a) Test 3 of Ti-6Al-4V. (b) Test 4 of Ti-6Al-4V.

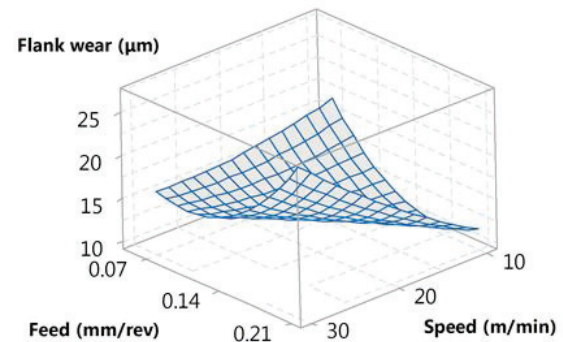


Figure 11. Tool flank wear following drilling of Ti-6Al-4V at test cessation.

$$\text{Flank wear (Ti)} = 45.0 - 0.955 \text{ Speed} - 372 \text{ Feed} + 0.0093 \text{ Speed}^2 + 904 \text{ Feed}^2 + 6.43 \text{ Speed} * \text{Feed} \quad (4)$$

The ANOVA for drill flank wear following test cessation is detailed in Table 8. It was found that the interaction between the cutting speed and feed rate was a significant factor affecting tool wear with a PCR approaching 35%. This was probably due to the fact that lower cutting speeds and feed rates prolonged the exposure of the drill to localised thermal and mechanical stresses and therefore enhanced tool wear.

Table 8. ANOVA of tool flank wear at test cessation.

Source	DF	Adj SS	Adj MS	F	P	PCR
Speed	1	60.167	60.167	6.64	0.062	25.9%
Feed	1	2.667	2.667	0.29	0.616	1.1%
Speed <sup>2</sup>	1	2.012	2.012	0.22	0.662	0.9%
Feed <sup>2</sup>	1	45.762	45.762	5.05	0.088	19.7%
Speed*Feed	1	81	81	8.94	0.04	34.8%*
Error	4	36.238	9.06			
Lack-of-Fit	3	34.238	11.413	5.71	0.296	
Pure Error	1	2	2			
Total	9	232.5				

\*Significant at the 5% level

#### 4. Conclusions and future outlook

- Feed rate was statistically significant in relation to exit burr size for all the workpiece materials evaluated while the quadratic terms for feed rate and cutting speed were also found to be significant when drilling Ti-6Al-4V.
- The hole out-of-roundness and diameter oversize relationship with cutting speed and feed rate did not fit the quadratic model of response surface. This suggests a highly non-linear variation and the presence of other controlling factors such as fixture/machine tool vibration and damping characteristics. In addition, lobed holes were produced, which suggest the occurrence of lateral tool deflection/vibration.
- The interaction between cutting speed and feed rate was statistically significant in relation to tool wear when drilling Ti-6Al-4V and tool flank wear was less than 30  $\mu\text{m}$  (after 60 holes) in all tests.

The current study was aimed at improving capability for minimising burr formation in order to reduce post drilling deburring operations. The next phase of research will involve comprehensive hole surface integrity evaluation together with the development of finite element models to predict burr formation when drilling various workpiece materials. The work is expected to be relevant particularly for structures comprising multilayer stack materials.

#### Acknowledgements

The authors would like to thank the School of Mechanical Engineering, University of Birmingham for the provision of a scholarship to A.M. Abdelhafeez. We are further indebted to Airbus Operations Ltd. (UK) and MAPAL Ltd. (UK) for the supply of workpiece materials and tooling together with additional financial and technical support.

#### 5. References

- [1] Aurich JC, Dornfeld D, Arrazola PJ, Franke V, Leitz L, Min S. Burrs—Analysis, control and removal. CIRP Ann - Manuf Technol 2009;58:519–42.
- [2] Sofronas A, Taraman K. Model development for exit burr thickness as a function of drill geometry and feed. SME Tech Pap 1976.

- [3] Ko S-L, Chang J-E, Yang G-E. Burr minimizing scheme in drilling. J Mater Process Technol 2003;140:237–42.
- [4] Pande SS, Relekar HP. Investigations on reducing burr formation in drilling. Int J Mach Tool Des Res 1986;26:339–48.
- [5] Stein JM, Dornfeld DA. Burr formation in drilling miniature holes. CIRP Ann - Manuf Technol 1997;46:63–6.
- [6] Karnik SR, Gaitonde VN. Development of artificial neural network models to study the effect of process parameters on burr size in drilling. Int J Adv Manuf Technol 2008;39:439–53.
- [7] Dornfeld DA, Kim JS, Dechow H, Hewson J, Chen LJ. Drilling burr formation in titanium alloy, Ti-6Al-4V. CIRP Ann - Manuf Technol 1999;48:73–6.
- [8] Kim J, Min S, Dornfeld DA. Optimization and control of drilling burr formation of AISI 304L and AISI 4118 based on drilling burr control charts. Int J Mach Tools Manuf 2001;41:923–36.
- [9] Galloway DF. Some experiments on the influence of various factors on drill performance. Trans ASME 1957;79:191–231.
- [10] Furness RJ, Wu CL, Ulsoy AG. Statistical analysis of the effects of feed, speed, and wear on hole quality in drilling. J Manuf Sci Eng 1996;118:367–75.
- [11] Abele E, Elsenheimer J, Hohenstein J, Tschanerl M. Influence of drill dynamics on bore quality. CIRP Ann - Manuf Technol 2005;54:83–6.
- [12] Min S, Kim J, Dornfeld DA. Development of a drilling burr control chart for low alloy steel, AISI 4118. J Mater Process Technol 2001;113:4–9.
- [13] Montgomery DC. Design and Analysis of Experiments. 8th Ed. Hoboken, NJ: Wiley; 2012.
- [14] Wijeyewickrema AC, Keer LM, Ehmann KF. Drill wandering motion: Experiment and analysis. Int J Mech Sci 1995;37:495–509.
- [15] Kuo CL, Soo SL, Aspinwall DK, Bradley S, Thomas W, M'Saoubi R, Pearson D, Leahy W. Tool wear and hole quality when single-shot drilling of metallic-composite stacks with diamond-coated tools. Proc Inst Mech Eng Part B: J Eng Manuf 2014;228:1314–22.